A New Methodology for Modelling the Failure Characteristics of Nuclear Graphites

Gary D. Kipling and Gareth B. Neighbour

Department of Engineering, University of Hull, Cottingham Road, Hull, United Kingdom. HU5 7RX

Introduction

Carbon materials commonly exhibit complex failure mechanisms. Nuclear graphite demonstrates non-linear failure characteristics and an unpredictable fracture path, thereby making it difficult to accurately and consistently model the material computationally. These complexities are due, in part, to the heterogeneity of the materials microstructure related to the 'filler' and 'binder' constituents. This work describes a new approach for modelling the failure of nuclear graphite through the application of finite element analysis (FEA) to a simulated microstructure model. Here, the authors present the outline methodology for simulating the crack propagation through an idealised graphite model with the resulting crack growth resistance curve and other facture parameters.

Methodology

The proposed methodology uses the FEA package ANSYS. Fig. 1 shows the methodology for crack propagation through progressive removal of elements. Suitable computational models are generated using the inbuilt creation tools in ANSYS. The model is then meshed before displacements and restraints are applied. An area of crack initiation is identified, based upon a threshold 'failure' stress, once a solution has been derived, although other criteria may be adopted in the context of 'controlled crack growth' such as:

- Single highest stressed element or average stress within a region of elements
- Strain energy
- Strain

Crack extension is simulated by removing the elements which meet the selected criterion. After the removal of all identified elements, the meta-data regarding the properties (stresses, strains, displacements, strain energy *etc.*) for each element in the model is output. This data is then used to predict the bulk properties of the test sample. Further propagation of the crack is achieved by increasing the crack-opening displacement applied to the model before it is re-solved and the process repeated.

Experimental

Initial tests were carried out using the computational methodology to schematically determine the viability of the procedure. The model used for the first iteration of experimental tests was a compact tension sample (CTS) as shown in Fig 2. The chosen geometry was identified as the most suitable due to its ability to promote controlled crack growth through the sample and the wealth of experimental data available especially with nuclear graphites, *e.g.* [1].

Dimensions of the model were consistent with those specified in ASTM E399 standard compact tension specimen [2]. The failure criterion for this test was a 1^{st} principle stress threshold value of 30 MPa (which corresponds to the elastic limit in experimental tests). When the stress value for an element increased above this value it was removed, thereby advancing the crack through the sample. The model is then retested until no elements exceed the threshold and then increments of 0.005 mm applied until the 'failure' criterion was exceeded, thus indicating the further onset of crack extension. It should be noted that no elements were removed below a displacement of 0.06 mm, which corresponds well with experimental data. As discussed, the finite element 'output' data from each iteration of the model can be used to predict bulk properties of the material. For example, the strain energy can be used to determine the applied force, F, at a given displacement, δ, thus predicting a force-displacement curve as in any experimental test, using the equation;

$$F = 2\frac{U}{\delta} \qquad [1]$$

where *U* is the total strain energy for the model.

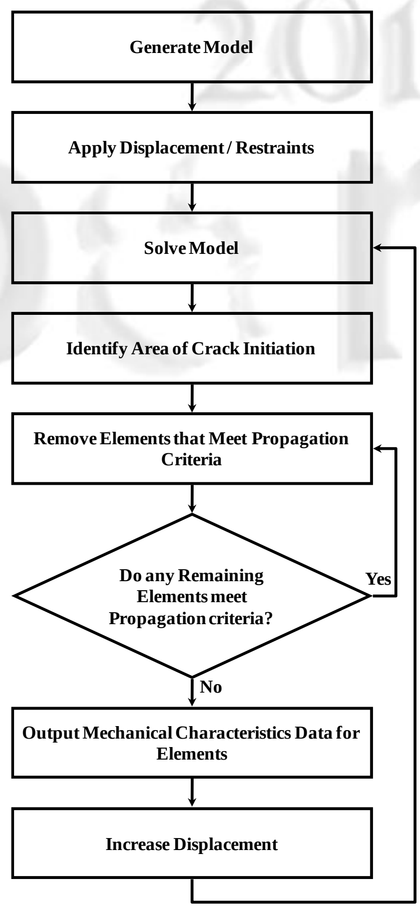

Fig. 1: Outline methodology for progressive removal of elements to simulate crack growth.

Results and Discussion

Fig. 3 shows a load - load point displacement curve generated using the CTS model. The model demonstrates a linear relationship until the simulated crack is initiated at 0.06 mm displacement. Removal of elements results in a decrease in the maximum stress (*i.e.* to below the propagation threshold). Upon increasing the displacement, further elements are subjected to a 1st principle stress exceeding 30 MPa and are therefore removed. Removal of elements causes an initial drop in calculated load at the given displacement. As the displacement is increased for the next iteration, the load again rises. As this process is repeated, the curve shows a reduced increase in load as the crack propagates further through the sample. It is also interesting to note that the model output suggests a 'saw-tooth' response reminiscent of shorts increments in crack growth often seen in experimental results. As the displacement is increased beyond 0.1mm, the cure shows a decrease in load as the displacement is increased. This response is analogous to the strain softening characteristics of nuclear graphite and other quasi-brittle materials. The 1st principle stress distribution in the model is shown at various stages of element removal in Fig 4.

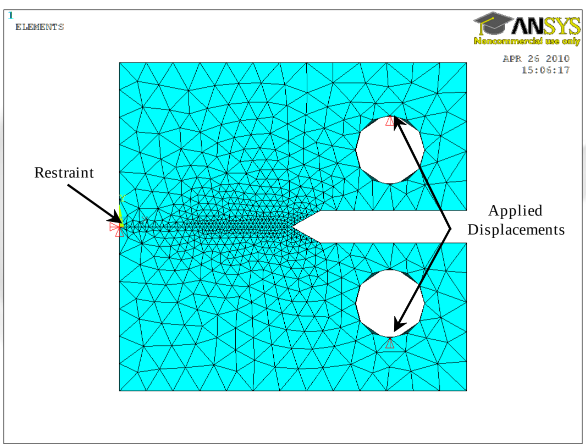

Fig. 2: Meshed compact tension model created in ANSYS showing applied restraint and displacements.

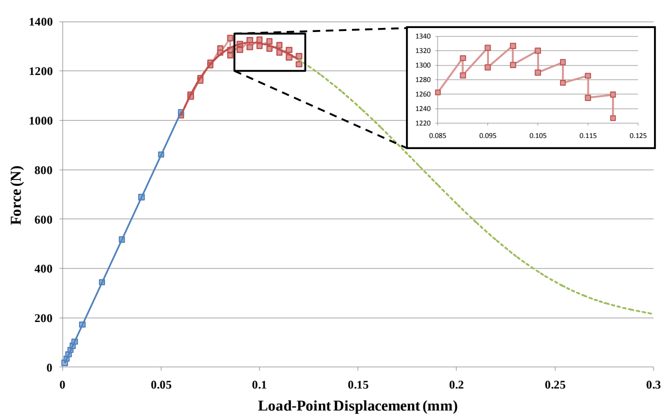

Fig. 3: Load-Load point displacement curve generated using the compact tension model and element removal methodology.

Conclusions and Future work

Application of this crack propagation methodology has been shown to generate mechanical data which can be used to determine failure characteristics of a sample. The model produced a schematic load - load point displacement curve which is characteristic of the failure curve expected from nuclear graphite. Currently, the model is limited to simulating crack growth through idealised material with the properties of an AGR nuclear graphite. Further progress and refinement of this methodology will see the introduction of a probabilistic nuclear graphite microstructure into the generated specimen and thus improve understanding and predictions of the fracture behaviour of large components made from brittle heterogeneous materials such as nuclear graphite.

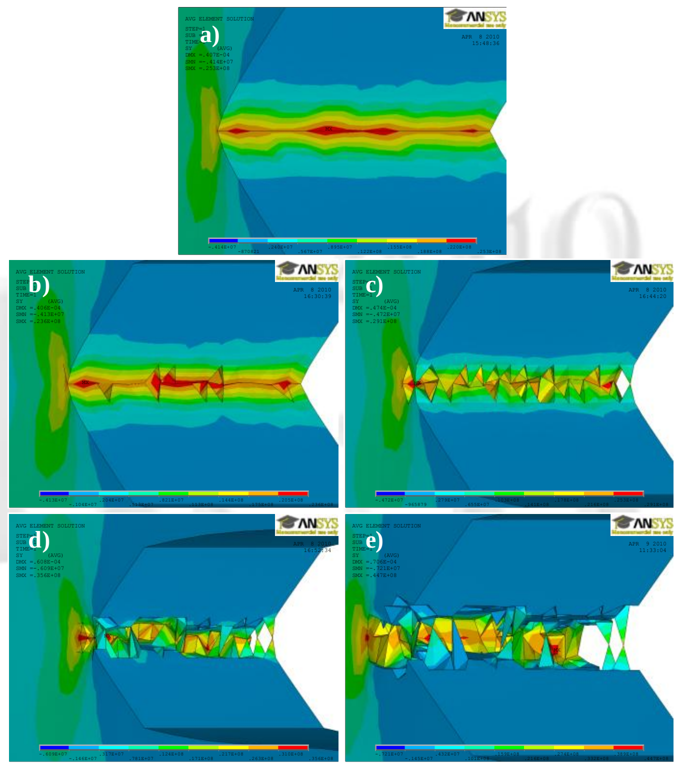

Fig. 4: Progressive removal of elements to simulate crack propagation. a) 0 elements removed, b) 22, c) 115, d) 395, e) 932.

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References

[1] Ouagne P, Neighbour GB, McEnaney B. Crack growth resistance in nuclear graphites. Journal of Physics D: Applied Physics 2002:35(9):927-934.

[2] ASTM E399-90: Standard Tests Method For Plane-Strain Fracture Toughness Of Metallic Material.